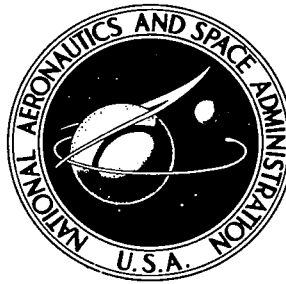


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## RESONANCE INTEGRALS OF RHENIUM FOR A WIDE RANGE OF SAMPLE SIZES

*by Clarence R. Pierce, Donald F. Shook,  
and Donald Bogart*

*Lewis Research Center  
Cleveland, Ohio*



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NASA TN D-4938

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NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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## ABSTRACT

Resonance integrals were measured for  $^{185}\text{Re}$ ,  $^{187}\text{Re}$ , and natural rhenium for foil and film thicknesses from 0.12 to about  $10^{-6}$  centimeter using both activation and reactivity methods. The thinnest samples yielded dilute resonance integral values of  $1790 \pm 60$ ,  $323 \pm 20$ , and  $866 \pm 35$  barns for  $^{185}\text{Re}$ ,  $^{187}\text{Re}$ , and natural rhenium, respectively. Resonance integrals calculated for the range of sample size using recently measured resonance parameters to 100 electron volts were found to be lower than the measured values by about 10 percent.

# RESONANCE INTEGRALS OF RHENIUM FOR A WIDE RANGE OF SAMPLE SIZES

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## SUMMARY

Resonance absorption integrals were measured for the isotopes rhenium-185, and rhenium-187, and for natural rhenium using both reactivity and activation methods. Natural rhenium foil thicknesses from about  $10^{-6}$  to 0.12 centimeter were used. The measured dilute resonance absorption integrals are  $1790 \pm 60$ ,  $323 \pm 20$ , and  $866 \pm 35$  barns for  $^{185}\text{Re}$ ,  $^{187}\text{Re}$ , and natural rhenium, respectively.

Resonance absorption integrals were calculated for the  $^{185}\text{Re}$  and  $^{187}\text{Re}$  isotopes and for natural rhenium for the range of sample sizes using a code based on the Nordheim method. The calculated resonance integrals were about 10 percent lower than the measured values. Likely causes for the lower calculated values are (1) an underestimation of the unresolved resonance contribution for  $^{187}\text{Re}$  which is based on statistics obtained for resonance levels to 100 electron volts only, and (2) a possibly low value for the measured neutron width of the 2.16-electron-volt resonance of  $^{185}\text{Re}$  the contribution of which dominates the resonance integral.

## INTRODUCTION

Rhenium has received attention as a possible alloy material in the construction of high temperature fast reactors, and therefore the nuclear parameters are of interest. The resonance absorption integrals of the naturally occurring rhenium isotopes and of natural rhenium are considered in this report. For very thin samples exposed to a neutron flux which varies inversely with neutron energy  $E$  the resonance integral is the well-known dilute resonance integral  $I_{\infty}$ :

$$I_{\infty} = \int_{E_{\text{Cd}}}^{\infty} \sigma_c(E) \frac{dE}{E} \quad (1)$$

where  $\sigma_c(E)$  is the microscopic capture cross section, and  $E_{Cd}$  is the cadmium cutoff energy. The measurements reported here are corrected to a sharp cutoff energy at 0.5 electron volt. For thick samples equation (1) is not applicable and an effective resonance integral that depends on the square root of the surface area to mass ratio  $(S/M)^{1/2}$  of the sample is measured. The effective resonance integral is a function of the capture cross section and of the self-shielded neutron flux in the finite sample. Published resonance parameters have been used to calculate effective resonance integrals for rhenium-185, rhenium-187, and for natural rhenium using the ZUT code based on the Nordheim integral method (ref. 1). In the calculation using ZUT, the assumption is made that the flux varies inversely with energy in the resonance region in the absence of the sample; for the resolved resonance region, the calculation using ZUT yields the resonance integral contribution for each resonance with the assumption of flux recovery between resonances. It is also assumed that there is no resonance overlap of the isotopes present in the natural metal sample. These assumptions appear to be valid for the low energy resonances of rhenium. For the unresolved resonance region of energy, a separate code TUZ is used (ref. 1), which makes use of s-wave statistics.

## SYMBOLS

A	adjustment factor for difference in fluxes with and without cadmium shield
B	saturated count rate for bare sample
C	saturated count rate for cadmium shielded sample
c	proportionality constant for use in determining resonance integrals from reactivity coefficients
D	level spacing, eV
E	neutron energy, eV
$E_{Cd}$	cadmium cutoff energy, eV
$E_0$	neutron resonance energy, eV
$E'_0$	neutron energy at lowest energy resonance, eV
g	statistical factor
$I_{eff}$	effective resonance integral, b
$I_{eff}^{calc}$	total calculated resonance integral for 0.5-eV cutoff, b

$(I_{\text{eff}}^{\text{calc}})_i$	calculated contribution to resonance integral from resonances in $i^{\text{th}}$ lethargy group, b
$I_{\infty}$	dilute resonance integral, b
$\Delta K/\text{NVK}$	reactivity coefficient for resonance absorber
$M$	mass of sample, g
$R$	cadmium ratio
$S$	surface area of sample, $\text{cm}^2$
$u$	lethargy
$\Gamma_n$	neutron scattering width, mV
$\Gamma_n^0$	reduced neutron width, mV
$\Gamma_{\gamma}$	neutron capture width, mV
$\epsilon$	counting efficiency
$\mu$	adjustment factor for difference of flux and cutoff energy from defined values
$\sigma_c$	capture cross section, b
$\sigma_{\text{th}}$	capture cross section at 0.0253 eV, b
$(\phi)_i$	calculated flux per unit lethargy
$(\phi^*)_i$	calculated adjoint per unit lethargy

Subscripts and superscripts:

$b$	without cadmium shield
$c$	with cadmium shield
$i$	index running from 0 to infinity
$j$	index running from 0.41 to infinity
$s$	standard sample
$x$	isotope under investigation

## METHODS OF MEASUREMENT

The reactivity and activation methods of measurement used here have been used previously and are discussed in detail in references 2 and 3. A uranyl fluoride solution

reactor with centrally located cadmium covered samples is used to measure relative reactivities. The reactivity measurements yield effective resonance integrals using the following relation:

$$\frac{\Delta K}{NVK} = - c I_{\text{eff}} \left[ \frac{\sum (I_{\text{eff}}^{\text{calc}})_i (\varphi_c)_i (\varphi_c^*)_i}{I_{\text{eff}}^{\text{calc}}} \right] \quad (2)$$

where  $\Delta K/NVK$  is the reactivity coefficient for the resonance absorber. The constant of proportionality  $c$  in mils per  $10^{24}$  atom-barn, relating reactivity to absolute resonance integrals, is determined by reference to gold as a standard. Reactivity coefficients for gold have been obtained for a wide range of sample sizes and these were used in reference 2 to obtain the constant  $c = 10.0 \pm 0.5$  mils per  $10^{24}$  atom-barn. The bracketed term is the calculated multigroup importance correction factor for perturbations to the inverse energy neutron flux caused by the cadmium cover,  $I_{\text{eff}}^{\text{calc}}$  is the total calculated resonance integral to 0.5 electron volt,  $(I_{\text{eff}}^{\text{calc}})_i$  is the calculated contribution to the resonance integral from resonances in the  $i^{\text{th}}$  lethargy group, and  $(\varphi_c)_i$  and  $(\varphi_c^*)_i$  are the calculated flux and adjoint per unit lethargy. The lethargy groups denoted by  $i$  cover the energy range from 0 to  $10^7$  electron volts.

For the activation measurements,

$$I_{\text{eff}}^x = \frac{(R - A)^s}{(R - A)^x} \frac{\sigma_{\text{th}}^x}{\sigma_{\text{th}}^s} I_{\text{eff}}^s \frac{\mu^x}{\mu^s} \quad (3)$$

where the superscript  $x$  represents the isotope under investigation,  $s$  represents the standard sample,  $\sigma_{\text{th}}$  is the radiative absorption cross section at 0.0253 electron volt, and  $R$  is the cadmium ratio

$$R = \frac{\frac{B}{\epsilon_b}}{\frac{C}{\epsilon_c}} \quad (4)$$

where  $C$  is the saturated count rate for the cadmium shielded sample,  $B$  is the saturated count rate for the bare sample, and  $\epsilon_c$  and  $\epsilon_b$  are the respective counting efficiencies. Also,

$$\mu = \frac{I_{\text{eff}}^{\text{calc}}}{\sum_i (I_{\text{eff}}^{\text{calc}})_i (\varphi_c)_i} \quad (5)$$

$$A = \frac{\sum_j (I_{\text{eff}}^{\text{calc}})_j (\varphi_b)_j}{\sum_i (I_{\text{eff}}^{\text{calc}})_i (\varphi_c)_i} \quad (6)$$

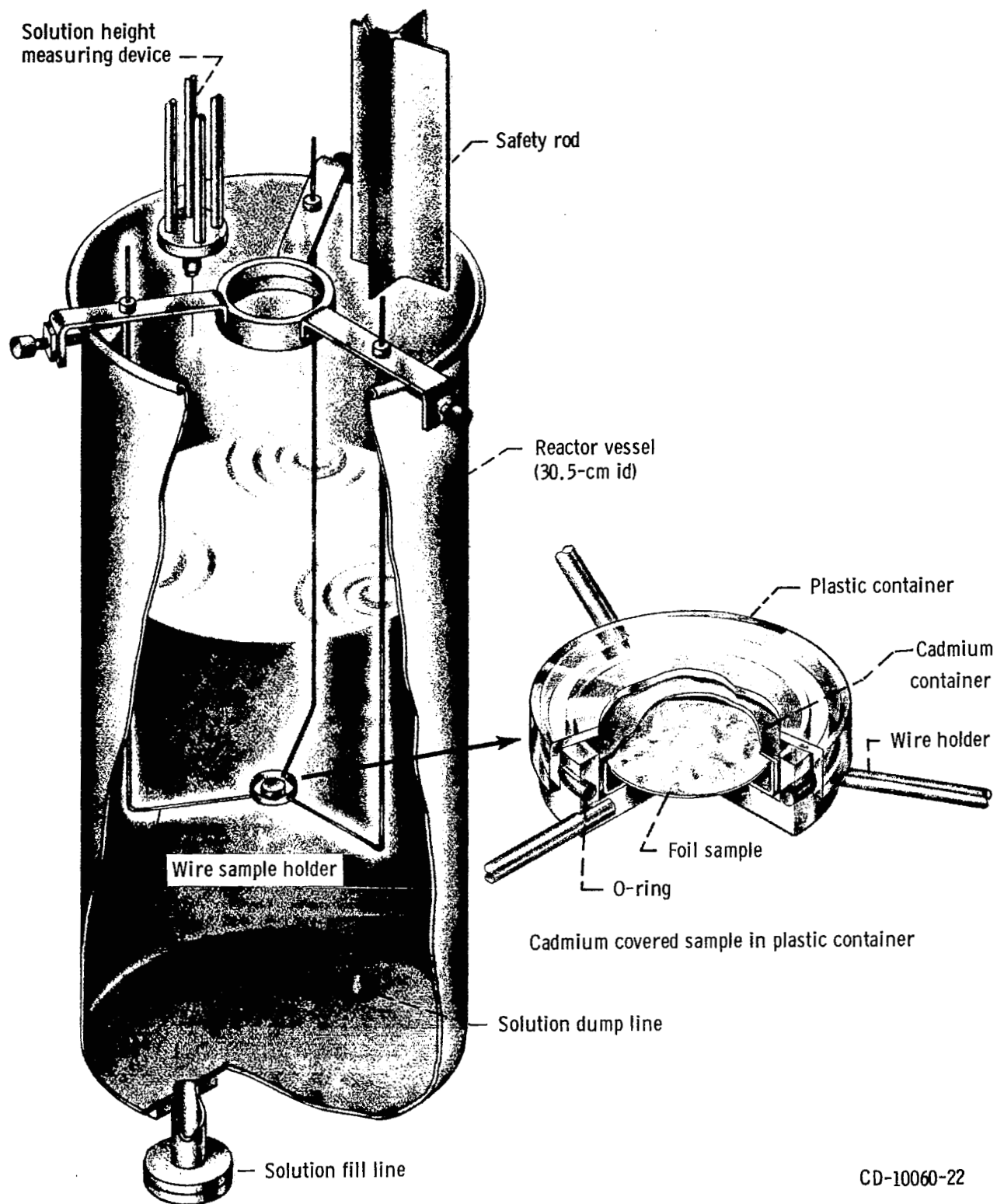
where  $(\varphi_b)_j$  is the calculated flux without the cadmium shield and the index  $j$  covers the energy range from  $10^7$  to 0.41 electron volt (lethargy 0 to 17). Rhenium cross sections at 0.0253 electron volt have been measured with good precision (ref. 4) and are reported to be  $114 \pm 3$  barns for  $^{185}\text{Re}$  and  $75 \pm 4$  barns for  $^{187}\text{Re}$ . A corresponding cross section value of  $98.7 \pm 1.8$  barns is used for gold (ref. 5). For thick samples, the sample thickness is chosen so as to ensure that the flux depression at 0.0253 electron volt produced by the gold standard is the same as that produced by the sample to be measured.

Natural rhenium metal samples were used throughout. The reactivity method yielded resonance integrals for natural rhenium but for reasons of accuracy, were limited to thicker samples of  $(S/M)^{1/2}$  smaller than 4 centimeters per gram $^{1/2}$ . The activation method was used to obtain resonance integrals for the individual rhenium isotopes. To avoid uncertainties due to bremsstrahlung contributions to the gamma activity, the samples used for activation were thinner than 0.4 gram per square centimeter. The resonance integrals for the separate isotopes were converted to elemental values by using the isotopic abundance ratios (37.07 percent for  $^{185}\text{Re}$  and 62.93 percent for  $^{187}\text{Re}$ ). The reactivity and activation methods together provide resonance integrals over a wide range of sample size.

## EXPERIMENT

The NASA ZPR-1, an unreflected solution reactor, was used for both the reactivity and activation experiments. The reactor is shown in figure 1 and is described in detail in reference 2. The fuel solution consisted of 93.3-percent enriched uranium-235 as uranyl fluoride in water. The fuel solution concentration was 7 percent by weight of uranyl fluoride with a hydrogen to uranium-235 atom ratio of about 500. Criticality was achieved by increasing the height of the fuel solution in the reactor vessel by small increments. The reactor was controlled entirely by variation of the solution height.





CD-10060-22

Figure 1. - Samples in reactor vessel.

Reactivity measurements and activations were made by suspending the samples at the center of the reactor vessel in the wire sample holder shown in figure 1. The samples were separated from the fuel solution by a cylindrical methacrylate plastic box with a 0.25-centimeter wall thickness. For the reactivity measurements and the epithermal activations, the samples were within a 0.89-millimeter-wall cadmium cover in the methyl methacrylate box. The maximum container size used was 6.3 centimeters in diameter and 1.6 centimeters in height. With the largest cadmium cover in place, the critical solution height was about 52 centimeters; without the cadmium cover, the height was about 46 centimeters. Solution height changes could be measured to  $\pm 0.2$  mil ( $\pm 5 \times 10^{-4}$  cm) using the micrometer lead screw height measuring device shown in figure 1.

The reactivity of a sample at the center of the core was determined as the difference between critical height  $\Delta H$  for sample in and sample out conditions. After several experiments were performed with different samples, the critical height with the sample holder and empty cadmium cover was redetermined to assure that reference reactor conditions were maintained. A reference critical solution height of 45.720 centimeters at a reference solution temperature of  $21.1^{\circ}\text{C}$  was maintained.

## Sample Preparation and Counting Techniques

The thin samples were prepared by vacuum depositing the metal on  $2.5 \times 10^{-3}$ -centimeter-thick aluminum. Five rhenium and two gold samples were prepared this way. The amount deposited was determined by weighing the aluminum foil before and after deposition. Errors in weights are estimated to be less than 10 percent. Since the same samples were used for the cadmium shielded as for the bare activations, errors in weight for these thin samples are not very important. The thick samples were 5.08 centimeter-diameter disks cut from rhenium sheet metal and from gold sheet metal.

The sample counting technique for the activation measurement was determined by the decay modes of the isotopes. The half lives and decay modes of the neutron activated rhenium isotopes are given in references 6 and 7. Because  $\gamma$ -rays are emitted with much lower intensity than  $\beta$ -rays, the thinnest samples were beta counted using a windowless  $2\pi$  proportional gas flow counter. The plateau was checked at regular intervals, and count rates were monitored using a depleted uranium sample.

Beta detection efficiency can be a problem for thicker samples because  $\epsilon_c$  will not be equal to  $\epsilon_b$  (eq. (4)), although the same sample is used for both bare and cadmium shielded activations. This efficiency difference is the result of neutron self-absorption in the sample (ref. 3). For this reason, the thicker samples were gamma counted, using a NaI (Tl) scintillation crystal and a single channel analyzer. The rhenium samples

were counted over the energy range 0.4 to 1.0 MeV, which included  $\gamma$ -rays accounting for 0.07 percent of the decays of  $^{186}\text{Re}$  and 5 percent of the decays for  $^{188}\text{Re}$ . The gold samples were counted over the energy range 0.3 to 0.9 MeV. The counting range for rhenium was chosen because the lower energy gamma rays, although of higher intensity, were attenuated significantly due to self-absorption, and they would have introduced an efficiency uncertainty in the results. Bremsstrahlung, produced by passage of the high energy beta particles through the sample, can be significant in the energy range counted. For this reason, the maximum sample thickness was 0.013 centimeter for the activation measurement.

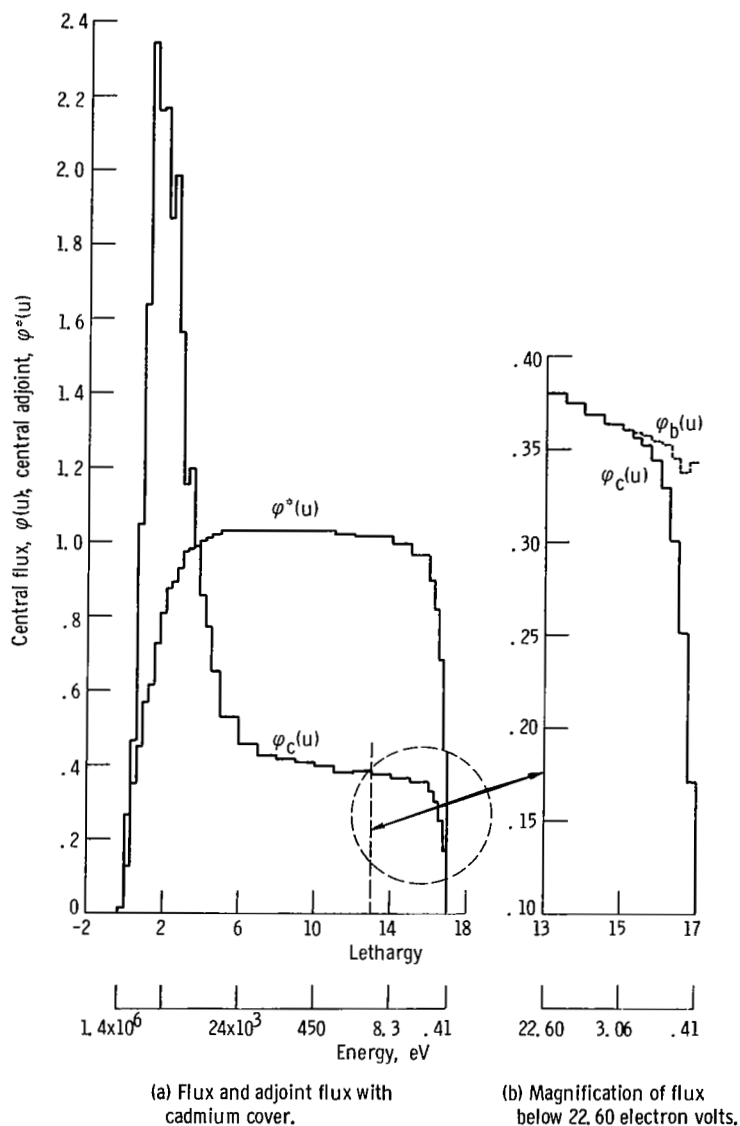


Figure 2. - NASA 2PR-1 central flux and central adjoint flux.

## METHOD OF CALCULATION

The calculated scalar and adjoint flux per unit lethargy within the cadmium cover at the center of the reactor are shown in figure 2. The calculations were made using the method described in reference 8. It can be seen that  $\phi(u)$ , the flux per unit lethargy, varies slowly with lethargy over the resolved resonance region. Although  $\phi^*(u)$ , the adjoint function, is constant over much of the resonance region, it declines rapidly to zero from about 3 to 0.41 electron volt because of the cadmium cover.

TABLE I. - IMPORTANCE WEIGHTED EFFECTIVE RESONANCE

### INTEGRAL OF NATURAL RHENIUM

Neutron energy range, eV	Product flux and adjoint	Sample size, $(S/M)^{1/2}$ , cm/g <sup>1/2</sup>					
		9.87		3.12		0.987	
		Effective resonance integral, $I_{\text{eff}}^{\text{calc}}$	Flux-and-adjoint weighted resonance integral, $I_{\text{eff}}^{\text{calc}}$	Effective resonance integral, $I_{\text{eff}}^{\text{calc}}$	Flux-and-adjoint weighted resonance integral, $I_{\text{eff}}^{\text{calc}}$	Effective resonance integral, $I_{\text{eff}}^{\text{calc}}$	Flux-and-adjoint weighted resonance integral, $I_{\text{eff}}^{\text{calc}}$
0.41 to 0.93	0.48	<sup>a</sup> 15.6	7.5	<sup>a</sup> 14.5	7.0	<sup>a</sup> 9.3	4.5
0.50 to 0.93	----	11.5	-----	10.7	-----	6.9	-----
0.93 to 3.29	.96	350.5	336.2	138.8	133.2	42.5	40.8
3.29 to 6.55	1.00	27.9	27.9	21.4	21.4	9.1	9.1
6.55 to 11.5	1.02	37.7	38.5	26.3	26.8	9.3	9.5
11.5 to 33.2	1.07	57.1	61.1	42.0	44.9	18.8	20.1
33.2 to 100.0	1.07	64.6	69.1	47.7	51.0	22.3	23.9
100 to 200	1.10	29.6	32.6	25.7	28.3	14.9	16.4
200 to 800	1.14	30.3	34.5	28.8	32.8	19.9	22.7
800 to 1600	1.17	6.9	8.1	6.9	8.1	5.7	6.7
1600 to 3200	1.19	4.0	4.8	4.0	4.8	3.6	4.3
Higher energy	1.34	6.5	8.7	6.4	8.6	6.2	8.3
Total	----	626.6	629.0	358.7	366.9	159.2	166.3
Importance correction factor, $[I_{\text{eff}}^{\text{calc}} \phi(u) \phi^*(u)] / I_{\text{eff}}^{\text{calc}}$		1.00		1.02		1.04	

<sup>a</sup>Not included in total.

TABLE II. - NEUTRON RESONANCE PARAMETERS FOR  
RHENIUM-185 (ref. 4)

(a) Resolved resonance parameters

Resonance energy, $E_0$ , eV	Capture width <sup>a</sup> , $\Gamma_\gamma$ , mV	Scattering width <sup>b</sup> , $\Gamma_n$ , mV
2.16	54±5	3.3±0.3
5.92	60±14	0.222±0.006
7.24	52±3	1.43±0.03
11.88	(53)	0.79±0.05
12.88	68±8	0.88±0.02
14.64	56±13	0.80±0.03
21.30	51±4	4.84±0.15
21.90	(53)	0.42±0.02
26.50	(53)	0.70±0.03
27.1	(53)	0.56±0.016
29.5	(53)	0.60±0.02
32.6	(53)	36.±8.
36.6	(53)	0.94±0.04
41.5	73±13	11.5±1.4
45.4	(53)	0.65±0.03
47.8	(53)	0.81±0.08
50.3	51±3	15.7±0.7
51.5	51±4	34.±6.
55.0	54±9	7.8±0.3
58.4	(53)	20.±2.
63.0	(53)	4.6±0.5
66.7	45±10	10.3±0.5
74.7	(53)	10.0±3.0
81.0	(53)	5.9±1.4
87.2	(53)	7.±2.
89.1	(53)	1.2±0.2
93.4	(53)	1.5±0.5
95.6	(53)	5.±1.
98.8	(53)	13.±7.

(b) s-Wave statistics

Average capture width, $\langle \Gamma_\gamma \rangle$ , mV	Average reduced neutron width, $\langle \Gamma_n^0 \rangle$ , mV	Average level spacing, $\langle D \rangle$ , eV	Statistical factor, g
53	1.03	2.9	0.5

<sup>a</sup>Values in parentheses are  $\langle \Gamma_\gamma \rangle$ . This value was used for those resonances where  $\Gamma_\gamma$  is not reported.

<sup>b</sup>Statistical spin factor is taken to be 0.5.

TABLE III. - NEUTRON RESONANCE PARAMETERS FOR

RHENIUM-187 (ref. 4)

## (a) Resolved resonance parameters

Resonance energy, $E_0$ , eV	Capture width <sup>a</sup> , $\Gamma_\gamma$ , mV	Scattering width <sup>b</sup> , $\Gamma_n$ , mV
4.42	51±2	0.375±0.004
11.14	63±6	2.08±0.08
16.07	59±9	0.660±0.014
17.58	57±5	2.05±0.04
18.52	60±10	0.69±0.03
24.8	(54)	0.131±0.010
32.0	71±7	10.0±0.4
33.9	51±14	1.12±0.04
39.4	55±2	12.4±0.5
46.9	(54)	0.10±0.01
47.5	(54)	5.±1.
53.5	57±6	6.1±0.3
58.9	(54)	2.1±0.3
61.0	61±6	29.±5.
63.7	(54)	2.2±0.3
69.5	63±6	26.±3.
73.7	49±4	70.±11.
75.0	63±15	29.±10.
78.1	(54)	1.6±0.2
79.1	79±50	2.8±0.2
85.1	65±12	9.3±0.7
87.60	(54)	7.±2.
91.80	(54)	1.8±0.6

## (b) s-Wave statistics

Average capture width, $\langle \Gamma_\gamma \rangle$ , mV	Average reduced neutron width, $\langle \Gamma_n^0 \rangle$ , mV	Average level spacing, $\langle D \rangle$ , eV	Statistical factor, g
54	1.30	3.0	0.5

<sup>a</sup>Values in parentheses are  $\langle \Gamma_\gamma \rangle$ . This value was used for those resonances where  $\Gamma_\gamma$  is not reported.

<sup>b</sup>Statistical factor is taken to be 0.5.

The method of calculating the importance correction factor (eq. (2)) is discussed in reference 2. The importance weighted effective resonance integrals of natural rhenium are shown in table I for three sample sizes. The sample size is expressed in terms of  $(S/M)^{1/2}$  ((surface area (cm<sup>2</sup>)/sample mass (g))<sup>1/2</sup>). The contribution to the resonance integral for energies below  $3/7E'_0$  where  $E'_0$  is the neutron energy at resonance maximum for the lowest energy resonance were calculated using the low energy cross sections of reference 4 and numerical integration. Contributions for the resolved region were calculated using the resonance integral code ZUT (ref. 1) discussed previously. For rhenium, the ZUT code sets the lower energy limit of  $3/7E'_0$ . Contributions for the "unresolved" regions were obtained using the TUZ code described in reference 1; for higher energies, the average cross sections of references 4 and 9 were numerically integrated. For the purpose of present calculations, the energy region where parameters for resolved resonances have not been measured ( $>100$  eV) is treated as unresolved.

Neutron resonance parameters used in the calculation are listed in tables II and III and are obtained from reference 4. Statistical spin factors for the more important resonances may be obtained from reference 10; however, no significant error is introduced by taking the factors to be 0.5 for these resonances.

The flux correction factors  $A$  and  $\mu$  (eq. (7)) for the activation experiment are obtained by the same method as that used for calculating the importance correction factor.

The calculated flux  $\phi_b(u)$  for the bare sample irradiations is shown in figure 2(b). The flux is significantly different from the flux within the cadmium cover  $\phi_c(u)$  between about 3 and 0.41 electron volt. Above 3 electron volts, there is no significant difference between  $\phi_c(u)$  and  $\phi_b(u)$ .

A correction for non- $1/v$  variation of the cross section below 0.41 electron volt was obtained by using a Maxwellian distribution for the thermal flux and the cross sections of reference 4. This correction resulted in a 4-percent reduction in the  $^{187}\text{Re}$  resonance integral and a 2-percent increase in the  $^{185}\text{Re}$  resonance integral.

## RESULTS AND DISCUSSION

The activation and reactivity resonance integral values for natural rhenium,  $^{185}\text{Re}$ , and  $^{187}\text{Re}$  are shown in tables IV(a), (b), and (c), respectively. The dilute values shown in the tables are the average of the values obtained for the samples with  $(S/M)^{1/2}$  greater than 100 centimeters per gram<sup>1/2</sup>. The measurements throughout this range of values of  $(S/M)^{1/2}$  show no change in the resonance integral beyond the error limits, as shown in figure 3. The dilute value may be compared with dilute values obtained by

TABLE IV. - MEASURED RESONANCE

## INTEGRALS

## (a) Natural rhenium

Sample thickness, $\text{mg}/\text{cm}^2$	Sample size, $(S/M)^{1/2}$ , $\text{cm}/\text{g}^{1/2}$	Resonance integral, b
0.04	Dilute	<sup>a</sup> 866±35
72.1	5.27	<sup>a</sup> 520±20
142.0	3.76	<sup>b</sup> 463±45
255.0	2.73	<sup>a</sup> 371±10
255.0	2.73	<sup>b</sup> 370±20
544.0	1.92	<sup>b</sup> 288±15
1053.0	1.38	<sup>b</sup> 241±15
2127.0	.97	<sup>b</sup> 172±10
4880.0	.64	<sup>b</sup> 120±5

## (b) Activation data for rhenium-185

Isotopic sample size, $(S/M)^{1/2}$ , $\text{cm}/\text{g}^{1/2}$	Resonance integral, b
Dilute	1790±60
8.65	960±40
4.48	628±30

## (c) Activation data for rhenium-187

Isotopic sample size, $(S/M)^{1/2}$ , $\text{cm}/\text{g}^{1/2}$	Resonance integral, b
Dilute	323±20
6.64	260±20
3.44	220±20

<sup>a</sup>Activation data.<sup>b</sup>Reactivity data.



others (refer to table V). Most of the published values, when adjusted to correspond to the gold resonance integral and thermal cross section values used here, agree within the stated error limits of the present experiments.

The resonance integral values shown in table IV are compared with calculated resonance integrals. Table VI shows the calculated resonance integral contribution for two sample sizes of  $^{187}\text{Re}$  and  $^{185}\text{Re}$  from four energy groups. The first group extends from the cutoff energy of 0.5 electron volt to the energy at which the resolved resonance calculation begins. The second group is covered by the resolved resonance calculation. For the third group the resonance parameters are unknown, and the contribution is due almost exclusively to s-wave neutrons. For the final group p-wave and higher  $l$ -wave neutrons also contribute to the resonance integral.

TABLE V. - SUMMARY OF EXPERIMENTAL VALUES OF  
RHENIUM RESONANCE INTEGRALS

Resonance integral, b	Reference	Method of measurement	Resonance integral for gold, $I_{\infty}^{\text{Au}}$ , b	Thermal absorption cross sections, b		Corrected <sup>a</sup> resonance integral, b
				Re $\sigma_{\text{th}}$	Au $\sigma_{\text{th}}$	
Rhenium-185						
1650±90	11	Two spectrum	1565	-----	----	1660±90
1753±90	11	Cadmium ratio	1565	-----	----	1764±90
1061±212	14	Cadmium ratio	1337	101	93	1330±212
<sup>b</sup> 1941	13	Activation	1558	-----	----	<sup>b</sup> 1963
1790±60	This work	Cadmium ratio	1575	114	98.7	1790±60
Rhenium-187						
308±20	11	Cadmium ratio	1565	-----	----	310±20
275±40	14	Cadmium ratio	1337	75.3	93	304±40
323±20	This work	Cadmium ratio	1575	75	98.7	323±20
Natural rhenium						
<sup>c</sup> 805±40	11	Two spectrum	1565	-----	----	810±40
<sup>c</sup> 842±50	11	Cadmium ratio	1565	-----	----	848±50
856±65	11	Capture gamma	1565	-----	----	862±65
694±125	12	Cadmium ratio	1558	84	96	723±125
<sup>c</sup> 566±117	14	Cadmium ratio	1337	85	93	687±117
866±35	This work	Cadmium ratio	1575	89	98.7	866±35

<sup>a</sup>Corrected for resonance integral and thermal cross section used in this work.

Error limits are not adjusted.

<sup>b</sup>Error limits not reported.

<sup>c</sup>Value obtained by combining isotopic resonance integrals.

TABLE VI. - CALCULATED RESONANCE INTEGRAL

## CONTRIBUTION FOR RHENIUM

(a) Sample size,  $(S/M)^{1/2} = 312 \text{ cm/g}^{1/2}$ 

Neutron energy group, eV	Effective resonance integral, b	Neutron energy group, eV	Effective resonance integral, b
Rhenium-187		Rhenium-185	
0.50 to 3.63	15	0.50 to 0.93	21
3.6 to 94	179	0.9 to 100.0	1592
94 to 3000	79	100 to 3200	67
Above 3000	7	Above 3200	8
Total	280	Total	1688

(b) Sample size,  $(S/M)^{1/2} = 3.12 \text{ cm/g}^{1/2}$ 

Neutron energy group, eV	Effective resonance integral, b	Neutron energy group, eV	Effective resonance integral, b
Rhenium-187		Rhenium-185	
0.50 to 3.63	14	0.50 to 0.93	20
3.6 to 94	104	0.9 to 100.0	344
94 to 3000	66	100 to 3200	58
Above 3000	7	Above 3200	8
Total	191	Total	430

Table VI shows that the unresolved contribution accounts for 28 percent of the resonance integral of  $^{187}\text{Re}$  for a  $(S/M)^{1/2}$  of 312 centimeters per gram<sup>1/2</sup> and 35 percent for a  $(S/M)^{1/2}$  of 3.12 centimeters per gram<sup>1/2</sup>. The corresponding unresolved contributions for  $^{185}\text{Re}$  are 4 and 13 percent, which are much lower than the values for  $^{187}\text{Re}$  because of the large  $^{185}\text{Re}$  resonance at 2.16 electron volts. Since  $^{187}\text{Re}$  constitutes 63 percent of natural rhenium, the unresolved resonances make a significant contribution to the resonance integral of natural rhenium. It would greatly improve the accuracy of the calculation if the resolved resonance region could be extended to a higher energy than the 100 electron volts reported in reference 4.

Figure 3 shows the resonance integrals as functions of sample size  $(S/M)^{1/2}$ . If the computer codes are used with resonance parameters and s-wave statistics as shown in tables II and III, the curves shown by the solid lines in figure 3 result. These calculated values show agreement with the measured values within the estimated error limits.

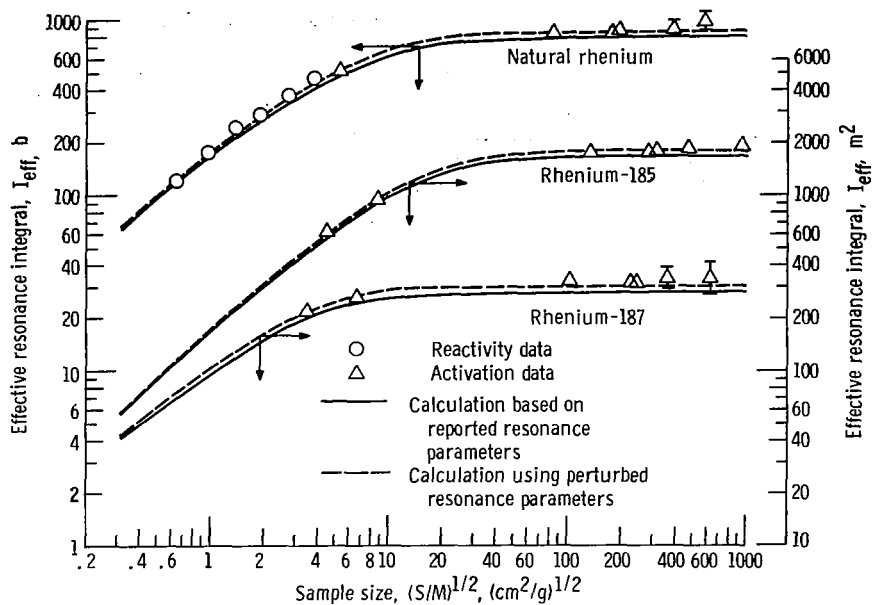


Figure 3. - Effective resonance integrals for natural rhenium and contained rhenium-185 and rhenium-187.

which indicates that the major contributions to the resonance integrals have been calculated correctly.

It may be noted, however, that the measured values all lie about 10 percent above the calculated curves. This could be accounted for if there were a number of rather large levels lying just above 100 electron volts, the energy to which the resonance parameters are known (ref. 4). It has been pointed out (ref. 4) that the strength function for natural rhenium obtained from the resolved resonance parameters is lower than the value obtained from fitting average cross section measurements in the kilovolt range; therefore, the average neutron width for s-wave levels may be larger than that obtained from the resolved data to 100 electron volts.

To explore likely sources of the differences between measurement and calculation, the calculations were performed using several values for the input parameters. It was found that values for the resolved resonance parameters of  $^{187}\text{Re}$  would have to be increased by an amount greater than the uncertainties in the measured values to achieve agreement for this isotope. In view of this, the unresolved calculation was redone for  $^{187}\text{Re}$  using the values for the s-wave statistics given previously, but with  $\langle \Gamma_n^0 \rangle = 2.2$  millivolts rather than 1.30 millivolts (see table III(b)). This value yielded the best agreement with the experimental data, and it gives a strength function value of  $3.7 \times 10^{-4}$  electron volt compared to the value of  $2.3 \times 10^{-4}$  electron volt obtained from the resolved resonances (ref. 4). It should be noted that an equivalent increase in the

unresolved resonance integral contribution for  $^{187}\text{Re}$  could be accounted for by a few large resonances just above 100 electron volts, the present resolved region upper limit. Therefore, this calculation does not provide conclusive evidence for an increased average reduced neutron width for  $^{187}\text{Re}$ .

For  $^{185}\text{Re}$ ,  $\langle \Gamma_n^0 \rangle$  would have to be about 5 instead of 1 millivolt (table III) to yield agreement with the present experimental data. This value is much larger than is required to fit the measured average cross sections in the kilovolt region. On the other hand, the total resonance integral of  $^{185}\text{Re}$  is sensitive to the value of  $2g\Gamma_n$  used for the important 2.16-electron-volt resonance. If this value is increased from 3.3 to only 3.5 millivolts, which is within the stated uncertainties in the measured value, and  $\langle \Gamma_n^0 \rangle$  is increased to 2.0 millivolts, agreement is obtained between calculated and experimental resonance integrals. The value of  $2g\Gamma_n$  for the 2.16-electron-volts resonance suggested here has a large uncertainty, since it includes both the uncertainty in the measured resonance integral, and also the uncertainty in value of  $\langle \Gamma_n^0 \rangle$  taken for  $^{185}\text{Re}$ .

## CONCLUSIONS

The resonance integrals of  $^{187}\text{Re}$ ,  $^{185}\text{Re}$ , and natural rhenium have been measured for a wide range of sample size and compared with calculated values. Agreement is within stated error limits. All measured values, however, lie about 10 percent above the calculated values for both  $^{185}\text{Re}$  and  $^{187}\text{Re}$ . A number of sources for the difference are possible. One likely source of the difference for  $^{187}\text{Re}$  is the large unresolved resonance contribution to the calculated integral. The indication is that the average reduced neutron width is larger than the value obtained from the analyzed resonances below 100 electron volts. In the case of  $^{185}\text{Re}$ , the major portion of the resonance integral for both thin and thick samples is supplied by the lowest positive energy resonance, and the total resonance integral is insensitive to the value for the reduced neutron width. One way to account for the discrepancy for this isotope is by increasing the neutron width for this resonance. The discrepancy for  $^{185}\text{Re}$  can be accounted for if the value of  $\Gamma_n$  for the important lowest positive energy resonance of  $^{185}\text{Re}$  at 2.16 electron volts is chosen to be 3.5 millivolts, which is slightly larger than the measured value of  $3.3 \pm 0.3$  millivolts reported.

Lewis Research Center,

National Aeronautics and Space Administration,

Cleveland, Ohio, August 30, 1968,

129-02-04-03-22.

## REFERENCES

1. Kuncir, G. F.: A Program for the Calculation of Resonance Integrals. Rep. GA-2525, General Atomic Div., General Dynamics Corp., Aug. 28, 1961.
2. Shook, Donald F.; and Bogart, Donald: Effective Resonance Integrals of Separated Tungsten Isotopes from Reactivity Measurements. Nucl. Sci. Eng., vol. 31, no. 3, Mar. 1968, pp. 415-430.
3. Pierce, Clarence R.; and Shook, Donald F.: Determination of Dilute  $^{186}\text{W}$  and  $^{184}\text{W}$  Resonance Integrals by Activation. Nucl. Sci. Eng., vol. 31, no. 3, Mar. 1968, pp. 431-439.
4. Friesenhahn, S. J.; Gibbs, D. A.; Haddad, E.; Fröhner, F. H.; and Lopez, W. M.: Neutron Capture Cross Sections and Resonance Parameters of Rhenium from 0.01 eV to 30 keV. J. Nucl. Energy, vol. 22, no. 4, Apr. 1968, pp. 191-210.
5. Friesenhahn, S. J.; Haddad, E.; Fröhner, F. H.; and Lopez, W. M.: The Neutron Capture Cross Section of the Tungsten Isotopes From 0.01 to 10 Electron Volts. Nucl. Sci. Eng., vol. 26, no. 4, Dec. 1966, pp. 487-499.
6. Gove, N. B.: A = 186-Ta, W, Re, Os, Ir, Pt, Au, Hg. Nucl. Data, Sec. B, vol. 1, no. 2, June 1966, pp. B1-2-1 to B1-2-22.
7. Ewbank, W. B.: A = 187-W, Re, Os, Ir, Pt, Au, Hg. Nucl. Data, Sec. B, vol. 1, no. 2, June 1966, pp. B1-2-23 to B1-2-52.
8. Fieno, Daniel: Transport Study of the Real and Adjoint Flux for NASA Zero Power Reactor (ZPR-I). NASA TN D-3990, 1967.
9. Stupegia, D. C.; Schmidt, M.; and Madson, A. A.: Fast Neutron Capture in Rhenium. J. Nucl. Energy, Parts A/B, vol. 19, no. 10, 1965, pp. 767-773.
10. Stolovy, A.: Spin Determinations of Neutron Resonances in Sb, Ta, Re, and Ir, Using Iron-alloy Targets. Phys. Rev., vol. 155, no. 4, Mar. 20, 1967, pp. 1330-1333.
11. Sher, R.; LeSage, L.; Connolly, T. J.; and Brown, H. L.: The Resonance Integrals of Rhenium and Tungsten. Trans. Am. Nucl. Soc., vol. 9, no. 1, June 1966, pp. 248-249.
12. Karam, R. A.; and Parkinson, T. F.: The Resonance Absorption Integral of Rhenium. Proceedings of the conference on Neutron Cross Section Technology. P. B. Hemmig, ed. AEC Rep. CONF-660303, bk. 1, 1966, p. 171.

13. Brown, H. L., Jr.; Connolly, T. J.; and Foell, W. K.: Effective Resonance Integrals and Interference Between Resonances of Indium-115, Gold, and Rhenium-185. Trans. Am. Nucl. Soc., vol. 5, no. 2, Nov. 1962, pp. 375-376.
14. Harris, S. P.; Muehlhause, C. O.; and Thomas, G. E.: Low Energy Neutron Resonance Scattering and Absorption. Phys. Rev., vol. 79, no. 1, July 1, 1950, pp. 11-18.